The springs of Lake Patzcuaro: chemistry, salt-balance, and implications for the water balance of the lake

James L. Bischoff, Isabel Israde-Alcantara, Victor H. Garduno-Monroy, Wayne C. Shanks III

Abstract

Lake Patzcuaro, the center of the ancient Tarascan civilization located in the Mexican altiplano west of the city of Morelia, has neither river input nor outflow. The relatively constant lake-salinity over the past centuries indicates the lake is in chemical steady state. Springs of the south shore constitute the primary visible input to the lake, so influx and discharge must be via sub-lacustrine ground water. The authors report on the chemistry and stable isotope composition of the springs, deeming them representative of ground-water input. The springs are dominated by Ca, Mg and Na, whereas the lake is dominated by Na. Combining these results with previously published precipitation/rainfall measurements on the lake, the authors calculate the chemical evolution from spring water to lake water, and also calculate a salt balance of the ground-water–lake system. Comparing Cl and $\partial^{18}O$ compositions in the springs and lake water indicates that 75–80% of the spring water is lost evaporatively during evolution toward lake composition. During evaporation Ca and Mg are lost from the water by carbonate precipitation. Each liter of spring water discharging into the lake precipitates about 18.7 mg of $CaCO_3$. Salt balance calculations indicate that ground water input to the lake is $85.9 \times 10^6 \, m^3$ and ground water discharge from the lake is $23.0 \times 10^6 \, m^3$. Thus, the discharge is about 27% of the input, with the rest balanced by evaporation. A calculation of time to reach steady-state

ab initio indicates that the Cl concentration of the present day lake would be reached in about 150 a.

1. Introduction

Many Latin American altiplano lakes are under severe environmental pressure due to increasingly intensive agriculture. Attempts at conservation and restoration of the lakes require accurate understanding of the many environmental factors, particularly those governing water balances. The center of the Tarascan civilization a thousand years before Columbus, Lake Patzcuaro, a picturesque tourist destination today, continues to support an agricultural and fishing economy on its shores and islands. Because of its economic importance, its limnology has been particularly well studied and monitored for the past half-century (Chacon-Torres, 1993; and Chacon-Torres and Muzquiz-Iribe, 1997, and references therein). Lake Patzcuaro is a 'C'-shaped lake (Fig. 1) with a long axis of about 20 km, a maximum width of 11 km, a
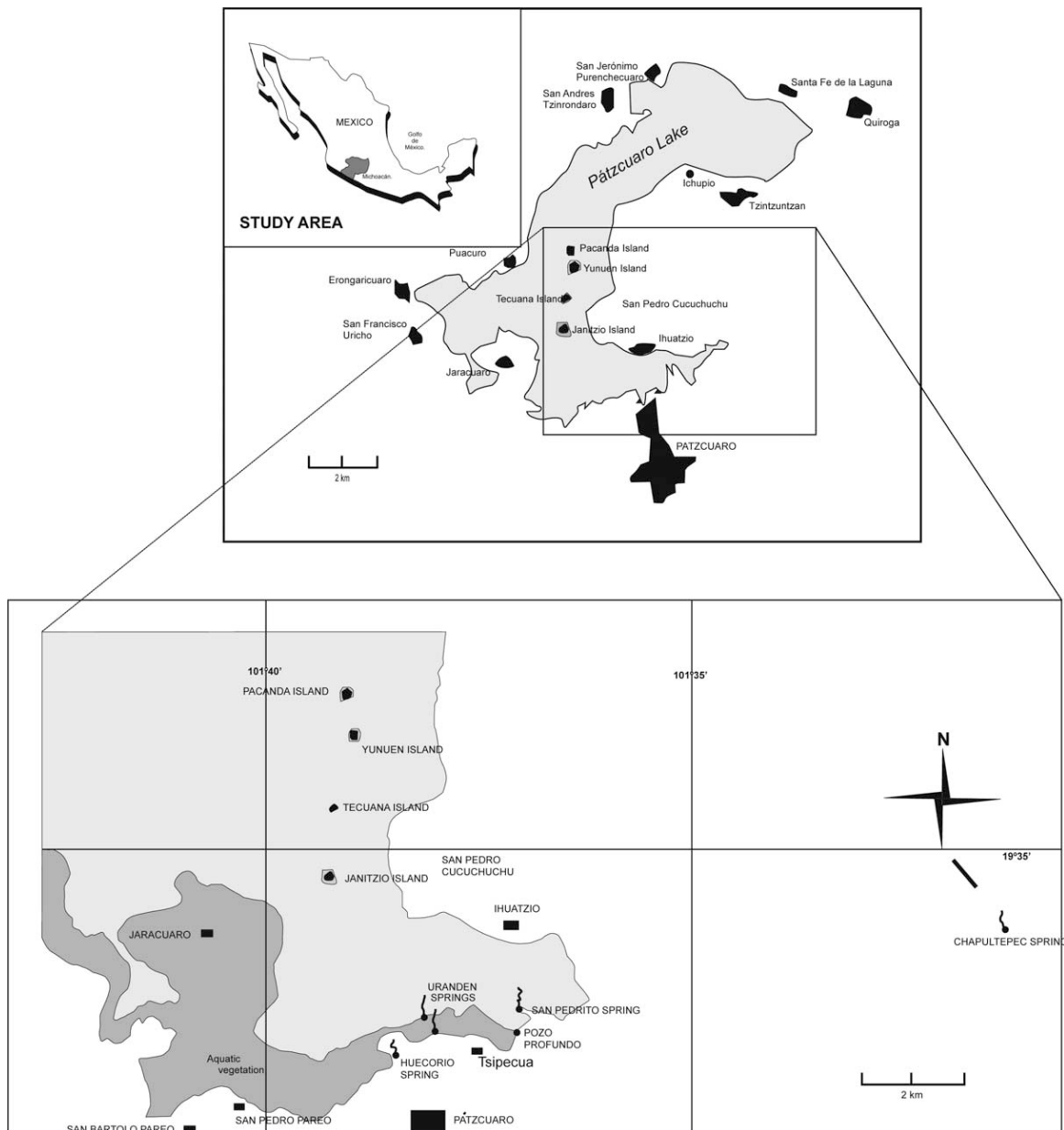
Fig. 1. Location of Lake Patzcuaro, and of South-shore springs sampled in present study. Dark grey pattern indicate areas of recent regression by the lake, now characterized by swampy aquatic vegetation.

mean depth of m, and lies at an elevation 2035 on shallow ground-water that occurs primarily during the the western edge of the volcanic central altiplano of summer rainy season. The lake level typically drops on Mexico (Chacon-Torres, 1993). The lake occupies

basin formed by the damming of pre-existing drainages by volcanic eruptions and associated uplift and faulting
(Israde-Alcantara, 1999). The bedrock is dominantly basalt and andesite. The lake has neither river input nor outlet, so its level appears to be maintained by flow of shallow ground-water that occurs primarily during the
summer rainy season. The lake level typically drops on the order of 0.9 during the winter–spring dry season. The only permanent sub-aerial springs occur at or slightly above the lake level along the southern shore near the town of Patzcuaro (Fig. 1), although some sub-lacustrine springs are seen to upwell in the SE sector of the lake. In what follows, the authors report on the chemistry and stable-isotope composition. Assuming the springs are representative of the ground-water input to the lake, a salt balance of the ground-water–lake system, and residence time and the fluxes of ground-water into and out of the lake are calculated.

2. Previous work

Bradbury (2000) presented a thorough literature review of the physiography, geology and climate of the lake basin, and of the limnology as part of his pollen, diatom, and geochemical study of a 15 m sediment core taken in the lake that spans the past 48 ka. He pointed out that the lake is particularly important in paleolimnological studies because it has apparently never been dry since at least the middle of the last glacial cycle. O'Hara et al. (1993) studied 21 shallow sediment cores from which they observed dramatically increased sediment accumulation beginning about 2500 a BP. Their attribution of this increase to accelerated soil erosion by intensive agricultural exploitation by pre-Columbian indigenous people has attracted much attention and controversy. For example, Fisher et al. (2003) ascribed accelerated soil erosion to low-population density, rather than intensive agriculture. Later landscape

stability was maintained during a period of population growth, urbanism, and increasing environmental modification. They trace the degradation of the present-day landscape to the Early Hispanic introduction of Euro-agro techniques.

Chacon-Torres and Muzquiz-Iribe (1997) established the water balance of the lake based on their thorough study of local climate, rainfall, evaporation and resultant e_ects on lake levels since 1939. Lake levels have varied seasonally only on the order of 1 m as a steady-state balance between rainfall, evaporation and recharge to the lake from the ground-water table. They found the mean annual evaporation over the

lake surface to be 186.3 x 10^6 m^3 whereas rainfall is

123.4 x 10^6 m^3 (Table 1). In the absence of any significant run-off to the lake, they reasoned that the

Table 1 Parameters related to Lake Patzcuaro water balance from Chacon-Torres and Muzquiz-Iribe (1997)

Catchment area = 803 km^2

Lake area = 126 km^2

Total area = 929 km^2

Lake volume = 628.5 x 10^6 m^3

Lake area annual precipitation = 123.4 x 10^6 m^3

Lake area annual evaporation = 186.3 x 10^6 m^3

Ground-water seepage = 62.9 x 10^6 m^3

Average annual temperature = 16.3 °C

Average relative humidity[a] = 59%

a: Estimated by analogy to Valley of Mexico.

difference, or 62.9 x 10^6 m^3 must be made up by ground-water flow, or seepage. Comparing this seepage to the rainfall over the entire catchment area of 803 km^2, they calculated that seepage of ground-water into the lake constitutes about 8% of the total catchment rainfall, and concluded that much of the catchment rainfall must be lost by evaporation.

Lake Patzcuaro's hydrochemistry has been relatively constant from the first analyses in 1941 to the present. Bradbury (2000) pointed out that to maintain a relatively constant salinity in the face of salts gained through continued evaporation, solutes must leave the lake through ground-water seepage out of the basin. A major objective of the present study is to quantify groundwater input and output fluxes.

3. Sampling of springs

During 2002, 6 springs in the Chapultepec-Uranden area of the south shore of the lake were sampled (Fig. 1). Samples were taken in May, the dry season during low flow, and again in August, the wet season during high flow. In addition, a sample of the lake water was taken in August in the middle of the lake off-shore of San Pedro Cucuchucho (Fig. 1) a location chosen to be sufficiently removed from any spring influence. During both times in situ pH, temperature and conductivity were measured. One spring, San Pedrito, could only be sampled in May because of inundation by the rising lake level in the summer. Dry-season flow rates were measured (via Marsh-McBirney flow meter) in 3 of the springs, Chapultepec (0.396 m^3/s), Huecorio and Uranden (both about 0.050 m^3/s). Wet-season flow rates are estimated to be approximately 10 times greater.

4. Analytical procedures

Water samples were analyzed for cations by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Total-dissolved CO_2 (sum of CO_3 + HCO_3 +H_2CO_3) was analyzed by acidification

followed by coulometry, and the other anions by ion chromatography. Samples for water isotopes ($\partial^{18}O$ and ∂D) were analyzed by isotope-ratio mass spectrometry. Water samples were prepared for H isotopic analyses using the Zn reduction technique, and for O isotope analyses using an automated CO_2 equilibration technique. Values of $\partial^{18}O$ and ∂D are relative to Vienna Standard Mean Ocean Water (VSMOW); they have reproducibility of approximately 0.1% and 1.0%, respectively. Results for chemistry and isotopes are shown in
Table 2.

Table 2 Isotopic and chemical composition (mg/l) of Lake Patzcuaro, and of springs discharging on the south shore of the lake

	Sample no.	Na	K	Mg	Ca
Huecorio Tzipecua spring	1	12.0	1.4	4.4	7.8
Huecorio Tzipecua summer	6	12.2	4.4	8.7	12.5
Uranden manantial spring	4	8.1	1.7	4.8	7.2
Uranden manantial summer	8	8.1	7.0	5.8	8.2
Uranden lago spring	2	7.8	2.3	4.5	7.7
Uranden lago summer	7	8.3	3.3	6.1	8.8
Pozo Profundo Spring	5	19.8	3.2	14.3	23.0
Pozo Profundo summer	9	19.3	10.2	17.0	24.6
San Pedrito spring	3	28.4	4.0	21.3	32.0
Chapultepec summer	10	9.7	3.7	7.1	9.3
Average spring		14.3	5.4	11.0	15.9
Lake[c]	11	183.9	51.0	37.0	17.7
Lake[d]		136.3	42.0	34.1	13.3

Springs sampled during dry season, May 2002 and again during wet season, August 2002.

[a] Total dissolved carbonate species as mg/l HCO3 (includes HCO3,CO3 and dissolved CO2).

[b] Total dissolved solids, mg/l.

[c] This study. Surface sample taken near Cucuchucho, 8/02.

[d] Average of 11 samples reported by Bridgwater et al. (1999).

5. Discussion

5.1. Spring and lake chemistry

Salinities (TDS) of the springs range from 132 to 430 mg/l averaging about 238 mg/l, whereas the lake water fluctuates between 729 and 1039 mg/l or about 3–4 times more concentrated than the springs (Table 2). There is surprisingly little di_erence in spring chemistry between the May and August sampling despite the large di_erences in flow rates. The anionic compositions of the springs and the lake are dominated by carbonate species with only minor Cl, and SO4. The cations of the springs are dominated by Ca, Mg and Na, with a minor amount of K. In contrast, Na dominates in the lake water, with Mg and Ca relatively diminished (Table 2, Fig. 2). The composition of the springs is entirely consistent with the chemical weathering of basaltic rock by carbonic acid solutions, a generalized reaction of which is

$$CO^2 + H_2O + \text{basalt (plagioclase; olivine; pyroxene)}$$
$$= \text{clay minerals} + Ca^{2+} + Mg^{2+} + Na^+ + HCO_3^-$$

Triangular plots of relative equivalents of cations and anions show the relationship of the springs to the lake water (Fig. 2). The spring waters evaporatively evolve toward the lake composition, and in the

process lose Ca and Mg relative to Na, presumably by the precipitation of carbonates. The degree of evaporation can be independently assessed using the stable isotope composition and also by Cl ion. Chloride is the only measured solute that is not involved in chemical reactions as a result of evaporation and mineral precipitation. Therefore, its increase in concentration in the lake water over that of the springs is an indication of the degree of evaporation that takes place as the spring water evolves into lake water. The authors observe (Table 2) that Cl in the present sampling of the lake water is 44.9 mg/l. Bridgwater et al. (1999) report chemical analyses of 15 samples of lake water taken during a single season (sometime before 1994?) with an average Cl content of 24.9 mg/l. Cl concentrations of about 20 mg/l are referenced for 1942 and 1973 by Bradbury (2000).

This difference in Cl concentration from the present value probably reflects the trend of declining precipitation that started in the early 1980s and continues today (Chacon-Torres and Muzquiz-Iribe, 1997). The present

authors deem the decline in precipitation affects the chemistry of springs and lake proportionally. In the calculations that follow the measured Cl of 44.9 mg/l will be used to represent the lake at the time of the present writing because in the calculations its chemical and isotopic composition are compared to chemical and isotopic compositions of the springs made at the same time.

On this basis it is noted that the Cl content of 44.9 mg/l is 3.74 times greater than that of the averaged spring water (12.0 mg/l). This means that 73.3% of the spring water is lost by evaporation. Comparisons of stable isotope compositions of the lake and springs below yield a comparable estimate of the degree of evaporation.

5.2. Stable isotope systematics

A plot of dD versus d^{18}O (Fig. 3) shows that samples from the springs that drain into the lake have isotope
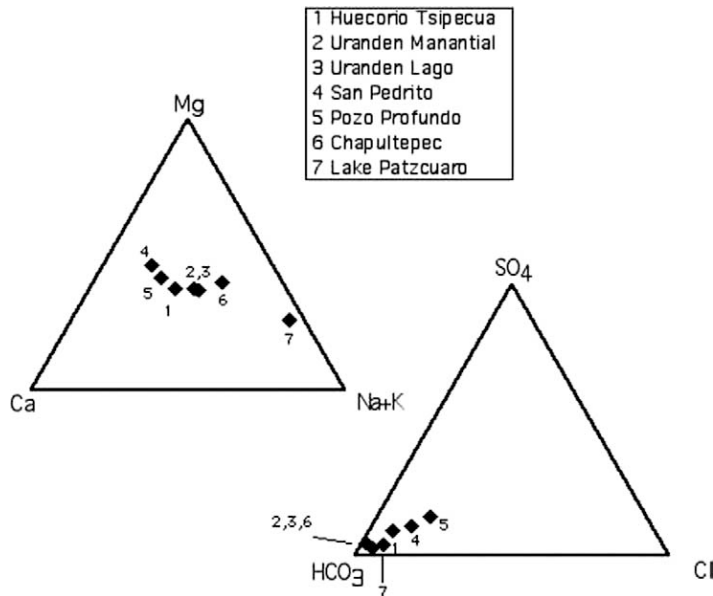

Fig. 2. Triangular diagrams of relative cationic and anionic compositions of Patzcuaro lake water and source springs. During evaporative evolution of spring waters to lake water Ca and Mg are lost as carbonate precipitates. Enrichment in Cl indicates spring waters lose 73.3% water during transformation to lake water.
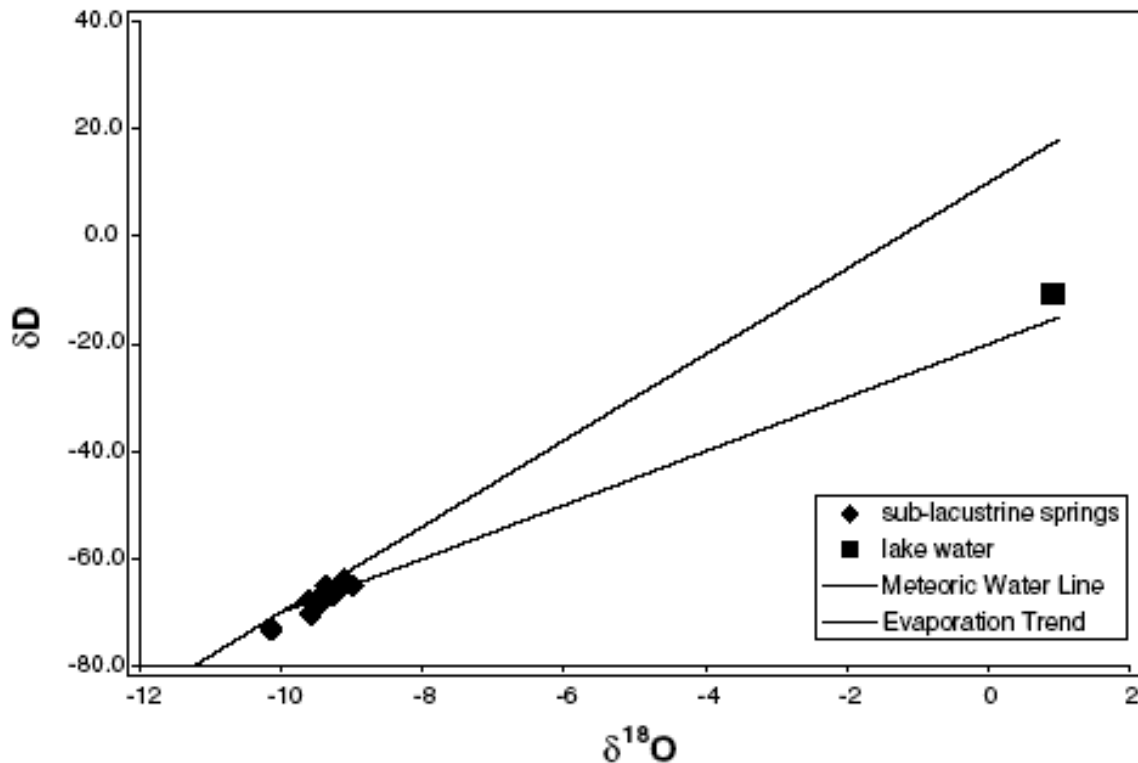
Fig. 3. Plot of composition of stable isotopes of H and O in Patzcuaro springs and lake water. Values of $\partial^{18}O$ and ∂D are relative to Vienna Standard Mean Ocean Water (VSMOW). The springs have isotope values of typical meteroic waters that plot on or near the global meteoric water line. In contrast, the lake water plots o_ the global meteoric water line exactly along the theoretical evaporation trend with respect to the springs, indicating 79.6% of the spring water is lost during evaporative evolution to lake water.

values of typical meteoric waters that plot on or near the global meteoric water line. The lake waters, in contrast, plot off the global meteoric water line of Craig (1961), and plot exactly along the theoretical evaporation trend.
Studies by Craig et al. (1963), Craig and Gordon (1965) and Gilath and Gonfiantini (1983) showed that the e_ects of evaporation, which are dependent on both kinetic and equilibrium liquid–vapor isotope

fractionation effects, can be calculated if temperature, relative humidity, and the isotopic values (O or H isotopes) of surface inflow waters and atmospheric vapor are known. In practice, the isotope values of atmospheric vapor are calculated assuming equilibrium with precipitation. Krabbenhoft et al. (1990) showed that the equilibrium assumption is valid, at least for $\partial^{18}O$ calculations. Parameters used in stable isotopic evaporation calculations are listed in Table 1. Using the equations in Gilath and Gonfiantini (1983) and the appropriate $\partial^{18}O$ data, the

authors calculate that spring water has evaporated approximately 79.6% in its evolution to lake water. This result is in reasonable agreement with the 73.3% calculated from Cl ion.

5.3. Mineral saturation

A calculation of the distribution of ionic species of the lake and wet-season spring composition given in Table 2 (pH measured in wet-season sampling only) using the computer program PHREEQC (Parkhurst, 1995) reveals that the spring waters have pressures of dissolved CO_2 (log pCO_2 averaging

-3.4 bar) very close to the atmospheric value of

-3.5 (Table 3). Log pCO_2 in the lake water

(-3.58, Table 2) is slightly less than atmospheric perhaps indicating photosynthetic utilization of dissolved CO_2, that likely drives carbonate mineral precipitation due to pH increase.

It is reasonable to conclude that the salt content of Lake Patzcuaro evolves from the input springs by a combination of evaporative concentration and precipitation of carbonate minerals. Speciation calculations further reveal (Table 3) that calcite and aragonite are close to saturation (average calcite log $IAP/K_{sp} \approx +0.14$ and aragonite -0.03) in the springs (saturation = 0). A similar calculation for the lake water shows strong supersaturation with these minerals (calcite

log IAP/K$_{sp}$≈+1.5, aragonite +1.4). Upper parts of cored sediments in Lake Patzcuaro are described as enriched in carbonates of Ca and Mg, and with an abundance of ostracode shells (Saporito, 1975). Thus, Mg and Ca carbonates are apparently precipitating as a consequence of the evaporative concentration of the spring waters.

Table 3 Calculated log pCO$_2$ and saturation states (log IAP/K$_{sp}$)[a] for CaCO3 minerals in Lake Patzcuaro, and of springs discharging on the south shore of the lake

	log pCO$_2$ [b]	Calcite	Aragonite
Huecorio Tzipecua	-3.34	0.14	-0.01
Uranden manantial	-3.45	0.05	-0.09
Uranden lago	-3.29	-0.14	-0.29
Pozo Profundo	-3.23	0.50	0.36
Chapultepec	-3.61	0.15	0.00
Spring average	-3.38	+0.14	-0.03
Lake Patzcuaro	-3.58	1.51	1.37

Calculations using PHREEQC (Parkhurst, 1995) speciation program with input concentrations from Table 2 using analyses from the sampling during the summer wet season.
[a] A value of 0 indicates saturation, >0 indicates supersaturation and <0 undersaturation.
[b] Atmospheric log pCO$_2$=-3.5.

5.4. Carbonate precipitation

The amounts of carbonate precipitation can be assessed by using the degree of evaporation calculated above. Multiplying the averaged concentrations of Mg, Ca, and carbonate species in the springs by the evaporation factor of 3.74, excesses for these components compared to the present lake-water concentrations are observed. These excesses

are taken as the amounts precipitated. These excesses are 4.1 mg/l for Mg and 41.9 mg/l for Ca. If the yearly flux of groundwater seepage is known then the total amount of carbonate precipitated yearly in the lake can be calculated and its sedimentation rate computed. In what follows the quantification of such flux is addressed.

5.5. Apparent salt residence time

In their water balance study Chacon-Torres and Muzquiz-Iribe (1997) carefully evaluated precipitation input and evaporation loss over the lake for the period from 1921 through 1986. They calculated the average annual precipitation over the lake to be $123.4 \times 10^6 \, m^3$ and the loss by evaporation to be $186.3 \times 10^6 \, m^3$, yielding a deficit of $62.9 \times 10^6 \, m^3$. They ascribed this deficit to be equal to the input of water from the surrounding catchment area by ground water seepage. If it is assumed that the only loss of water from the lake is by evaporation, then the salinity of the lake must be increasing with time. The present authors consider the time it would take to accumulate the Cl observed in the lake today assuming the input is the seepage value of $62.9 \times 10^6 \, m^3$. This time is considered the residence time of the salt and is given by

$$R_{Cl} = M_{Cl} / A_{Cl}; \quad (1)$$

where M_{Cl} is the total mass of Cl in the lake and A_{Cl} is the annual input of Cl to the lake. The mass of Cl dissolved in the lake today is 2.82×10^{10} g (44.9 mg/l, Table 2, times the volume of the lake, $628.5 \times 10^6 \, m^3$, Chacon-Torres and Muzquiz-Iribe, 1997). The annual flux of Cl to the lake from seepage is 7.6×10^8 g/a (spring-water Cl concentration times the annual seepage flux, or 12.0 mg/ l, Table 2, times $62.9 \times 10^6 \, m^3$). Dividing the total amount of Cl in the lake by the annual flux of Cl yields $R_{Cl} = 37$ a. This is the apparent residence

time of Cl in the lake. Such a short apparent residence time demonstrates there must be significant ground-water drainage out of the lake.

Moreover, the relatively little variation in lake salinity over the past centuries leads to the conclusion that the lake is in a steady-state condition with respect to inputs and outputs of dissolved salts.

5.6. Steady-state calculation

Assuming the Cl in the lake is indeed at steady-state concentration, the input and output fluxes of the lake are calculated. Thus, the total annual evaporation-pre-cipitation di_erence determined by Chac on-Torres and M

uzquiz-Iribe (1997), ST ($62.9 \times 10^6 \, m^3$) is taken to be equal to the di_erence between seepage in, Si, and seepage out, So

$$S_T = S_i - S_o. \quad (2)$$

For steady-state Cl concentration, the flux of Cl into the lake must equal the seepage flux of Cl out of the lake

$$C_i S_i = C_o S_o, \quad (3)$$

where Ci is the concentration of Cl in the springs and ground-water flow (12.0 mg/l), and Co is the concentration of Cl in the water seeping out of the lake. Because seepage out of the lake must be the lake water, then Co must be the same as the Cl concentration in the lake itself (44.9 mg/l). Substituting (2) into (3) results in

$$S_i = 85:9 \times 10^6 \, m^3/a,$$

$$S_o = 10^6 \, m =a: 23.0 \times 10^6 \, m^3/a.$$

Thus, the out seepage, or discharge, is about 27% of the input seepage, and this amount is enough to keep the Cl content of the lake in steady state.

5.7. True residence time of Cl

As above, the residence time of Cl in the lake is given by (1), and MCl is as before, but ACl is given by the input seepage Si (as

calculated in the previous section) times Cl concentration in the spring waters

$R_{Cl} = M_{Cl}/[S_i C_i] = 27.4$ years.

5.8. Time to steady state

With this information, the question is addressed of how long, with the present fluxes of water and salt would it take to achieve steady-state salt composition. Starting with a lake containing no dissolved salts, a time-dependant function for C_L the concentration of Cl as it accumulates in the lake is sought. It is assumed that the present Cl input is constant, but the outflow is considered as variable. The accumulation of Cl in the lake is given by $V_L dC_L/dt$, where V_L is the volume of the lake. Thus, the differential equation describing the process is

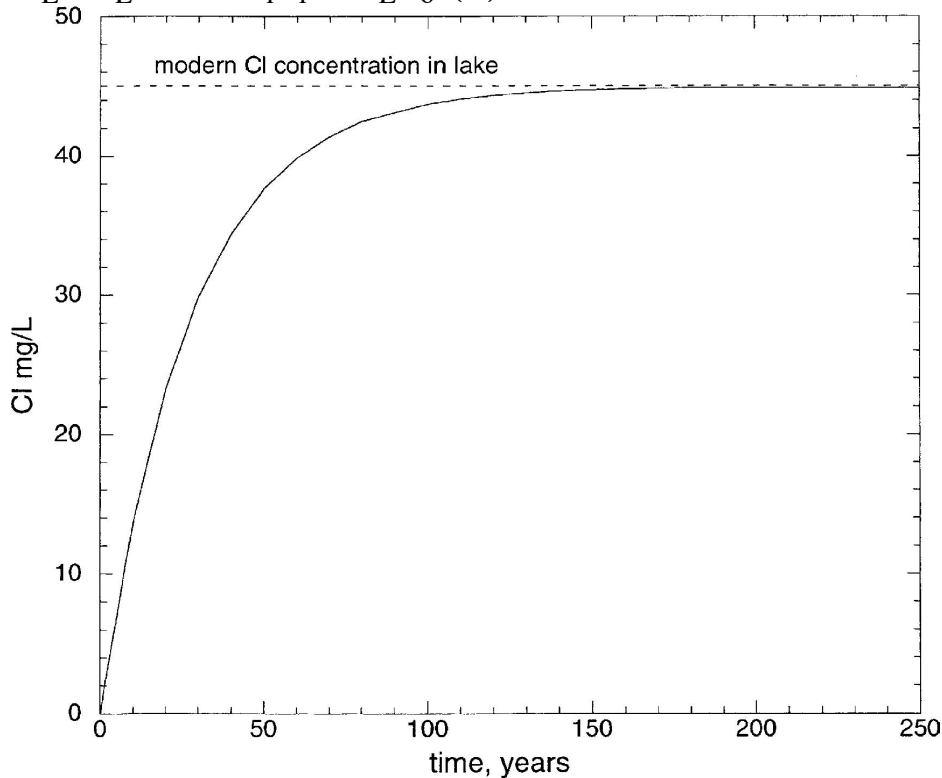$$V_L dC_L/dt = C_i S_i - C_L S_o \quad (4)$$

modern Cl concentration in lake

Fig. 4. Plot of Cl concentration in Patzcuaro lake water with time as calculated from Eq. (4), assuming zero Cl in the lake at time zero,

and present day salt inputs and outflows. The time to reach the present day Cl concentration, or steady state, is about 150 a.

This equation defines the time-variable buildup of Cl in the lake as equal to the constant seepage input minus the time-variable seepage output. Solving (4) using Laplace transforms, and substituting in the numerical values for V_L, C_iS_i, and S_o and setting $C_L = 0$ at $t = 0$, results in

$C_L = 44.91[1 - \exp(-0.0365t)]$, (5)

where C_L is in units of mg/l and t is in a. A plot of C_L versus t (Fig. 4) shows that the concentration of the present day lake will be reached in about 150 a, and the concentration will remain in unchanged steady state thereafter.

5.9. Carbonate sedimentation rate

The accumulation rate of $CaCO_3$ in the lake can now be calculated, given the magnitude of the decrease in Ca during evolution of spring water to lake water, and knowing the input rate of the springs. Thus, from above, the figure of 41.9 mg of Ca precipitated for each liter of lake water translates to 11.2 mg/l of spring water. This means that each liter of spring water produced 18.7 mg of $CaCO_3$. Multiplying by the annual input of spring water Si yields 16.1 x 10^8 g/a of $CaCO_3$ forming in the lake. Dividing this figure by the area of the lake (Table 1) yields an average accumulation rate of $CaCO_3$ of 1.27 g/cm^2/10^3 a. O'Hara et al. (1993) in their study of 20 short cores taken throughout the lake estimated inorganic (carbonate, organic free) sediment accumulation rates at various intervals over the past 2500 a. The authors' averaging of their data for the entire 2500 a indicates an average rate of about 15.8 g/cm^2/10^{3}a.

Comparing the present authors' estimate of the accumulation rate of $CaCO_3$ to this figure indicates that $CaCO_3$ should make up about 7.4

wt% of the sediment. The data of Saporito (1975) in his geochemical study of the 15 m core of Bradbury (2000) showed that $CaCO_3$, mostly in the form of ostracods, is abundant only in the top 2 m (ca. last 3000 a), below which $CaCO_3$ makes up only 1% or less of the sediment in the entire core. The present authors' averaging of his analyses of the top 2 m (20 samples) results in 10.1 wt% $CaCO_3$, a figure entirely consistent with the estimate of 7.4 wt% above, considering the errors inherent in such averaging.

The increased abundance of $CaCO_3$ in the top-most 2 m corresponds to the zone of dramatically increased sediment-accumulation beginning about 2500 a BP observed by O'Hara et al. (1993) and Fisher et al. (2003), attributed to the beginnings of early settlement. Perhaps agriculture significantly increased chemical weathering of basaltic soils, thereby increasing the flux of Ca to the lake.

6. Summary and conclusions

The study of the chemical and isotopic composition of Lake Patzcuaro and its shoreline springs allows the following conclusions as shown in Fig. 5:

1. TDS of the lake (700–1039 mg/l) is about 3–4 times greater than the springs (132–430 mg/l). Spring chemistry and TDS show only small variance from dry to rainy season despite the large differences in flow rates.

2. The springs are dominated by Ca, Mg, and Na, whereas Na dominates in the lake. Bicarbonate is the major anion in both springs and lake. The composition of the springs is consistent with the chemical weathering of basaltic rock by carbonic acid.

3. Cl in the lake water (44.9 mg/l) is 3.74 times greater than in the springs, indicating that about 73.3% of the spring waters is lost as spring waters evaporatively

evolve toward the lake composition. Comparison of $\partial^{18}O$ compositions of the springs and lake indicate 79.6% of the spring water is lost during evaporative
evolution to lake water, in good agreement with the calculation based on Cl.

4. During evaporation Ca and Mg are lost from the water by the precipitation of carbonates. Each liter of spring water discharging into the lake produces about 18.7 mg of $CaCO_3$.

5. Speciation calculations show that calcite and aragonite are close to saturation in the springs (average log IAP/K_{sp} = ± 0.14 and -0.03) whereas the lake is strongly supersaturated with these minerals (log IAP/K_{sp} ≈ +1.5 and +1.4).

6. The relatively small variation in lake salinity over the past centuries indicates that the lake is in a steady-state balance of inputs and outputs of dissolved salts. Such steady state requires that water is leaving the lake via ground water discharge. The Cl concentrations of springs and lake can be considered with previous data on evaporation/precipitation on the lake to allow calculation of ground water input to the lake. Ground-water input to the lake is 85.9 x 10^6 m³/a and ground-water discharge from the lake is 23.0 x 10^6 m³/a. Thus, the discharge is about 27% of the input, an amount that is sufficient to keep the Cl content of the lake in steady state.

7. Calculations for time to reach steady-state ab initio show that the Cl concentration of the present day

lake would be reached in about 150 a.

8. Based on the ground-water fluxes and the spring/lake differential of Ca/Cl, the rate of CaCO3 precipitation in the lake is calculated to be 16.1×10^8 g/a. Dividing by the area of the lake indicates an accumulation rate of 1.27 g/cm^2/10^3 a in the sediment, or about 7.4 wt% of the recent sediments. This compares with approximately 10 wt% $CaCO_3$ observed in the top 2 m of cored sediment.
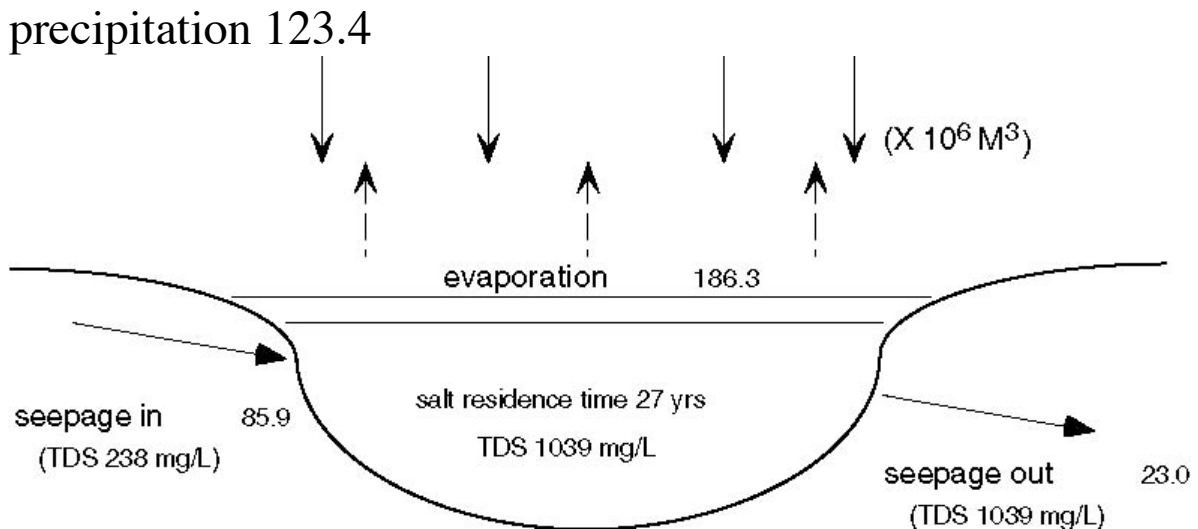
precipitation 123.4

Fig. 5. Annual water balance for Lake Patzcuaro.

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